FISSION TRACK THERMOCHRONOLOGY OF SOUTHEASTERN AUSTRALIA: UNIQUE PERSPECTIVES ON THE EVOLUTION OF OUR CONTINENTAL MARGINS AND MOUNTAINS*

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The accumulation of radiation damage from the spontaneous nuclear fission of ^{238}U is the basis of a thermally-sensitive geological dating technique which can be applied to common uranium-bearing minerals. Fission tracks in the mineral apatite are stable over geological time only at relatively low temperatures, below about 120°C, which are characteristic of the upper few kilometres of the Earth's crust. Fission track ages and track length distributions reflect the cooling history of rock masses that have passed through this upper-crustal domain. Broad regional patterns of fission track data are primarily controlled by large scale earth movements which initiate cooling in rocks through denudation at the Earth's surface. New interpretive techniques now enable these thermal and tectonic processes to be quantified and mapped out in considerable detail.

Studies in southeastern Australia using these methods reveal a striking imprint of tectonic activity related to continental breakup on the eastern and southern margins of Australia. A major element in the patterns is an overall decrease in fission track age towards the continental margins indicating higher palaeotemperatures and generally greater depths of erosion in this direction. In detail, however, the pattern is more complex than this and a number of regional variants are visible. In western Victoria there is an abrupt transition in behaviour which appears to terminate the breakup style characteristic of most of eastern Australia. Tasmania shows a generally deeper erosional level which may reflect its position within the evolving rift system during the separation of Australia and Antarctica.

THE accumulation of radiation damage from the spontaneous nuclear fission of ^{238}U is the basis of a geological dating technique which can be applied to a number of common uranium-bearing minerals, such as apatite and zircon. This simple method of geological dating was first described over thirty years ago (Price & Walker 1963) and has undergone a rapid development, particularly over the past fifteen years, both in terms of understanding the fundamental systems involved and in the diversity of its geological applications (see for example Wagner & van den Haute 1992).

Advances in defining the long-term stability of fission tracks at elevated temperatures and in modelling the response of the fission track dating system to changing temperatures have opened up what is now the major domain of application of fission track techniques—thermal history analysis, or thermochronology. Fission track thermochronology involves the using of fission track record in natural mineral systems to reconstruct the contrasting thermal histories which have occurred in various geological environments. The method is now applied across a wide range of geological studies, most significantly in analysing the thermal history of sedimentary basins, the tectonics of young mountain belts, and the evolution of rifted continental margins. The purpose of this paper is to briefly review the application of fission track thermochronology in southeastern Australia.

FISSION TRACK DATING

When a uranium nucleus contained in a natural mineral decays by spontaneous nuclear fission, the energy released is largely carried away as kinetic energy by the two fission fragments produced. These two highly energetic, and highly charged, particles fly apart from each other through the surrounding crystalline lattice and produce a single linear trail of radiation damage, known as a 'fission track'. The damaged region making up the fission track is highly chemically reactive compared to the surrounding undamaged material. As a result, fission tracks can be enlarged by a simple chemical etching procedure until they can be observed and measured by optical microscopy. The etching of fission tracks is illustrated diagrammatically in Fig. 1.

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The number of tracks revealed in this way on a polished surface of a mineral grain will be proportional to the time over which tracks have been accumulating, and the amount of uranium present. A thermal neutron irradiation procedure is used to artificially induce a second set of fission tracks, the number of which is proportional to the uranium concentration. The ratio, then, of the number of spontaneous fission tracks to the number of induced tracks gives a measure of geological age.

FISSION TRACK ANNEALING AND MODELLING

An important aspect of fission track dating is that the radiation damage making up the tracks is stable over geological time only at relatively low temperatures. As temperatures increase, the radiation damage making up the tracks is repaired by a diffusional process known as fission track annealing. This does not occur suddenly but rather takes place progressively over a broad temperature interval called the fission track annealing zone. The effect of geological annealing is that the fission track age becomes gradually reset, eventually reaching zero above the critical temperature at which the tracks are completely erased. Such a reduction in the apparent fission track age is accompanied by a progressive shortening of the tracks which can be measured to monitor the degree of annealing that has occurred (Gleadow et al. 1986).

The lengths of fission tracks are all very similar when first produced so that the observed distribution of lengths after annealing contains a record of the variation in temperature that has occurred over the lifetime of the host mineral. The underlying kinetics of fission track annealing are now well understood, at least for some minerals, from quantitative laboratory annealing experiments (e.g. Laslett et al. 1987; Green et al. 1989) and a variety of geological studies in well controlled environments. The resulting annealing models enable a detailed reconstruction of the thermal histories of rocks from the observed patterns of fission track lengths and apparent ages (Gleadow 1990; Gallagher 1995).

Fission track annealing occurs over a different temperature interval for each of the minerals used for fission track dating. Fission tracks in the common calcium-phosphate mineral apatite, for example, are stable over geological time only at temperatures below about 120°C. Such temperatures are characteristic of the upper few kilometres of the Earth's crust so that apatite ages reflect the cooling history of rock masses as they pass through this upper-crustal domain. Usually these apparent ages display little relationship to the original formation ages of the rocks but often reflect large scale earth movements which initiate episodes of cooling through erosion at the Earth's surface.

Fig. 2 shows a hypothetical cooling history from 300°C down to an ambient surface temperature of 20°C over a time period of 360 Ma. The

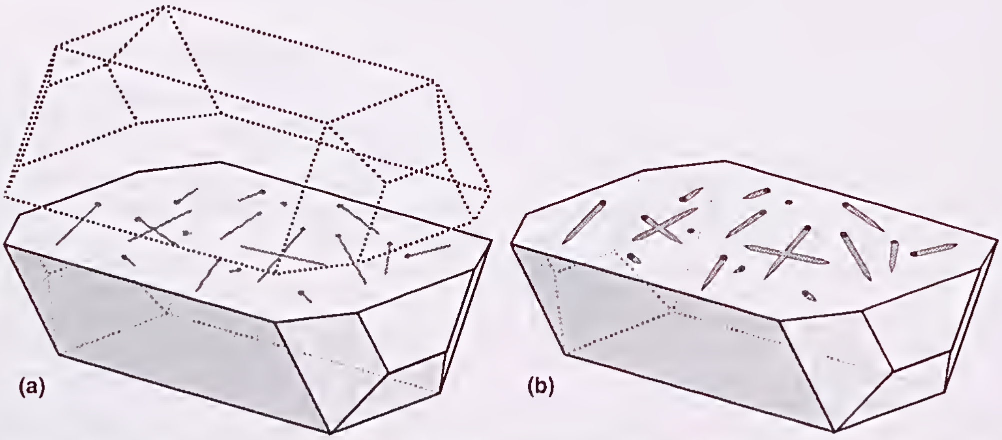

Fig. 1. Fission tracks are revealed in a crystal of a uranium-bearing mineral, such as apatite, by first cutting and polishing a smooth surface through the crystal (a). Fission tracks that cross this surface are then accessible to chemical etching which enlarges the tracks until they can be seen under an optical microscope (b). Fission tracks in apatite are etched in dilute nitric acid and have a needle-like shape. They measure about 16 μm in length and 1–2 μm across.

temperature-time path shows an initial rapid cooling, followed by very slow cooling between about 300 and 100 Ma and then rapid cooling again between 100 and 80 Ma. The diagram also shows calculated fission track ages and fission track length distributions for two minerals, apatite and zircon, calculated using the annealing model of Gallagher et al. (1995). The fission track annealing zone for zircon occurs at much higher temperatures and the shape of the track length distribution reflects the simple, rapid cooling of the host rock through this range. The zircon apparent age directly reflects the rapid cooling through the zircon annealing zone and may closely approximate the formation age of an igneous rock at even higher temperatures.

Cooling through the apatite annealing zone in Fig. 2 is more complex and the fission tracks recorded by the apatites resolve into two distinct components reflected in the bimodal length distribution. The shorter peak reflects those earlier formed tracks which pre-date the rapid cooling at about 100 Ma and have all been severely shortened by annealing at relatively high temperatures. The longer peak, in contrast reflects those tracks which have formed since about 80 Ma at relatively low temperatures. The apatite apparent age in this case is a mixture of both these components of tracks and does not directly indicate the timing of any particular geological event. Such mixed ages are relatively common and the interpretation of a suite of apatite ages depends critically on an understanding of the associated track length data.

Using these modelling techniques it is possible to reconstruct thermal histories which match the fission track data in a particular sample. Applying this to many samples throughout a broad area allows the overall pattern of regional cooling events to be established which can then be interpreted in terms of past tectonic and thermal activity, and patterns of surface denudation.

FISSION TRACK THERMOCHRONOLOGY IN SOUTHEASTERN AUSTRALIA

Studies in southeastern Australia over the past twenty years using these methods have revealed a striking imprint of tectonic activity related to continental breakup on the eastern and southern margins of Australia (e.g. Moore et al. 1986; Dumitru et al. 1991; Foster & Gleadow 1992; Hill et al. 1995). The overall pattern of apatite

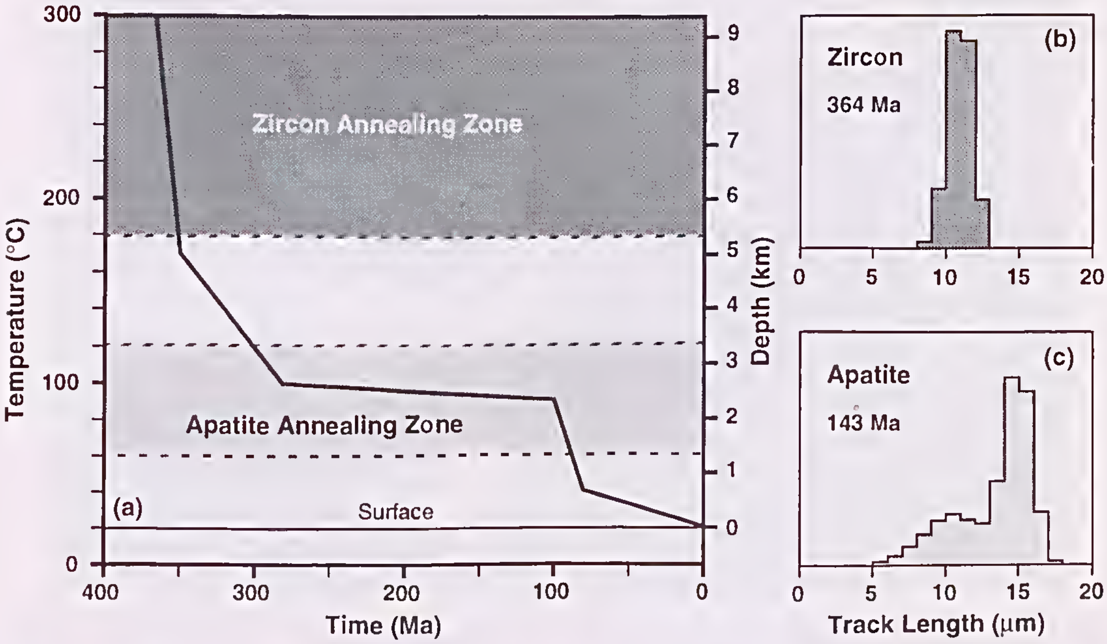

Fig. 2. A hypothetical thermal history for a rock showing a two-stage pattern of cooling from about 300°C over the last 360 million years (a). The diagram also shows the fission track annealing zones for the minerals zircon and apatite. The histograms (b) and (c) show the distributions of fission track lengths and apparent fission track ages for these two minerals calculated according to the modelling procedures of Gallagher (1995).

fission track ages in the Palaeozoic basement rocks of this region is shown in Fig. 3. The oldest apparent ages (up to 300 Ma or more) are associated with the inland regions of far-western Victoria or in the eastern highlands. Much younger apparent ages (down to 100 Ma or less) are found towards the continental margins. In general, the younger ages reflect later episodes of Mesozoic (mostly Cretaceous) cooling on a background of late Palaeozoic cooling ages. Intermediate apparent ages are frequently mixed ages as revealed by their distributions of track lengths (Moore et al. 1986).

The explanation for this pattern is that the eastern continental margin has been uplifted in a broad flexure towards the coast during the period of continental rifting leading up to the opening of the Tasman Sea by sea-floor spreading, about 80 million years ago (Moore et al. 1986). Erosion of the newly developed continental margin

Fig. 3. The distribution of apparent fission track ages in apatites from Palaeozoic basement rocks around southeastern Australia (modified and updated after Moore et al. 1986 and Dumitru et al. 1991). The apparent ages show a broad regional variation from maximum values in excess of 300 Ma to minimum values of less than 100 Ma. On the mainland the youngest apparent ages invariably occur in a relatively narrow strip adjacent to the rifted continental margins and surrounding the Bass Strait Basins. In general, apatite ages from Tasmania are significantly younger than those on the mainland.

has allowed rocks near the coast to cool from temperatures that were previously within or above the apatite fission track annealing zone. The youngest apatite ages observed have been completely reset around this time and are broadly similar to the ages of the oldest adjacent oceanic crust as determined from sea-floor magnetic anomaly patterns (Weissel & Hayes 1977; Shaw 1978). Along the east coast the apatite ages near the coast show a tendency to become younger from south to north. O'Sullivan et al. (1995) have suggested that this may reflect the progressive opening of the Tasman Sea in that direction from about 80 to 60 million years ago.

The youngest ages are generally associated with long narrow length distributions characteristic of relatively rapid cooling. This indicates that in some coastal areas rocks now exposed at the surface were at temperatures of just over 100°C during continental breakup in Early to Middle Cretaceous time. Assuming a typical geothermal gradient of 25–30°C, this implies that erosion of up to 3–4 km has occurred in some areas since that time. The possibility that higher thermal gradients may have existed at this time allows the amount of denudation inferred to be reduced but probably to no less than about half these figures.

Similar patterns are observed around the margins of the major sedimentary basins in Bass Strait which were also formed during the main phase of continental rifting in the Cretaceous. The youngest apparent ages exposed in Palaeozoic rocks of southern central Victoria and in the older sediments of the Otway Basin are similar to those along the east coast. These younger ages broadly correspond to cooling during the development of the basins and may be associated with an early, limited phase of slow sea-floor spreading in the Southern Ocean during mid-Cretaceous time (Cande & Mutter 1982). The much later onset of rapid sea-floor spreading between Australia and Antarctica at about 45 Ma appears to have left no discernible imprint on the pattern of fission track ages.

TASMANIA

Tasmania (Fig. 3) shows generally much younger apatite ages than those observed on the mainland, even though in most cases these are also obtained from rocks formed during the Palaeozoic (Hill et al. 1995). This suggests that generally deeper erosional levels are exposed in Tasmania which may reflect its central position within the evolving rift complex during the continental breakup phase. The Island was completely surrounded by developing rift systems in the Cretaceous during the early phases of separation between the three large continental blocks of Australia, Antarctica, and the Lord Howe Rise/New Zealand. It is possible that the continental margin effects observed on the mainland may therefore have had an additive influence in Tasmania.

Another factor which is unique to Tasmania is the development of the very large and extensive

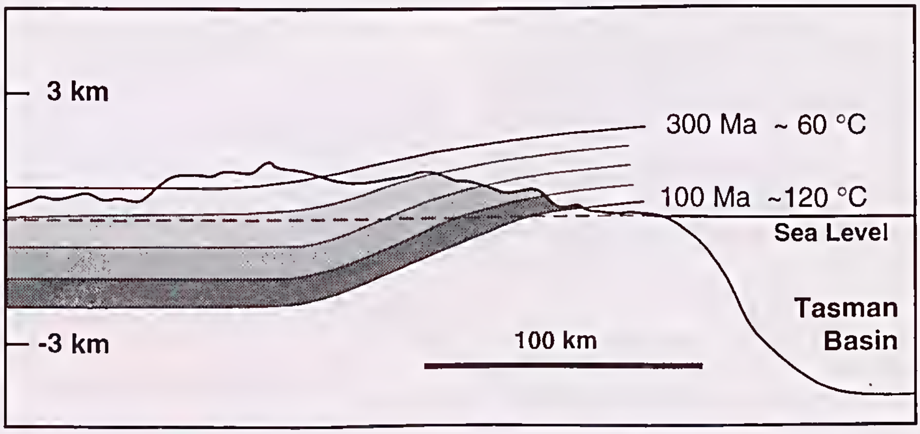

Fig. 4. A diagrammatic cross-section of southeastern Australia across the highlands to the continental margin in southern NSW. The shaded contours shows zones of decreasing apparent fission track age in apatites and how these are thought to be tilted upwards towards the coast in a broad flexure of the crust. The contours may also be taken to represent increasing palaeotemperatures in the crust during the Cretaceous (after Dumitru et al. 1991).

dolerite sills there during the Jurassic. These would have had the effect of raising temperatures across virtually the whole island to the point where it would be unlikely that fission tracks would survive in apatite. In this situation the entire pattern of apatite ages must post-date the Jurassic and are therefore starting from a much lower maximum than observed on the mainland. A similar ceiling effect caused by widespread Jurassic igneous activity has been observed in northern Victoria Land in Antarctica by Fitzgerald & Gleadow (1988).

WESTERN VICTORIA

In western Victoria there is an abrupt transition in behaviour which appears to terminate the structural style characteristic of the continental margin of most of eastern Australia. This can be seen as a marked change in the pattern of apatite fission track ages as shown in Fig. 3. West of this transition a completely different structure of the continental margin is apparent with no evidence for the broad crustal flexure found everywhere to the east (Foster & Gleadow 1992, 1993). This pattern is associated with extremely subdued topography which is typical of most of the southern margin of Australia and quite unlike the rugged eastern highlands which parallel the rifted margin to the east.

The transition in crustal architecture in western Victoria displays many of the characteristics predicted for an upper plate–lower plate boundary in the large-scale detachment model of Lister et al. (1991). Under this model the development of a continental margin is dominated by the formation of a major low-angle normal fault, or detachment, cutting obliquely through the continental lithosphere. One side of the developing rift, the lower plate, is then drawn out from beneath the other upper plate in an extensional style that is markedly asymmetrical. This model is significantly different from earlier models in that it predicts that the structure of the two separating plates will be different and that the polarity of the asymmetry may change periodically along the length of a rifted margin.

The transition in fission track pattern across western Victoria is relatively sharp and appears to follow a much older, Early Palaeozoic, boundary between the Delamerian and Lachlan Fold Belts. It is thought that this old crustal scale weakness may have been reactivated during Mesozoic rifting. The existence of this inherited weakness in the continental crust may also have played a fundamental role in locating the major transform plate boundary along the west coast of Tasmania which then transferred extension to the south of Tasmania during continental rifting. As a result the island remained as part of Australia, rather than Antarctica, despite the early phase of rifting through Bass Strait. The transform boundary is preserved today as the Tasman Fracture Zone which traverses the Southern Ocean to northern Victoria Land in Antarctica which was formerly adjacent to western Victoria prior to continental breakup.

SNOWY MOUNTAINS

The Snowy Mountains reveal a later modification of the regional architecture of the eastern continental margin with a structure dominated by large fault blocks elevated to varying degrees above the surrounding region, a structure still reflected in the present landscape (Cox et al. 1994). Overall uplift of the mountains is greatest on their western side, near Mt Kosciusko, and gradually steps down to the east (Kohn et al. 1994). Apatite ages of approximately 90 million years on the western side of the mountains probably date the onset of renewed tectonic activity in the eastern highlands generally, following a long period of quiescence during the late Palaeozoic and early Mesozoic. However, much of the present day relief of the mountains in this area is probably related to later, Tertiary, movements which have occurred along reactivated Palaeozoic faults. The uplift may be a response to the change in the crustal stress regime in this area from extension to the mild compression which now characterises southeastern Australia.

CONCLUSIONS

Fission track studies on the evolution of southeastern Australia have added considerably to our understanding the structural and geomorphic response of continents to extensional tectonic processes which occurred during the breakup of the former supercontinent of Gondwana. They have also made the area a major reference point for similar work being undertaken on rifted continental margin environments elsewhere in the world.

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